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Chaos-enhanced transport in cellular flows - such as those generated within cavities by a top free-flowing stream - have been studied with the long term objective of devising means to increase the rate of transport between surfaces and bulk flows. Chaotic advection is generated experimentally by periodic modulation of the free stream velocity. We find that transport occurs only near reattachment points of wall-attached streamlines. Detailed local measurements of transport in these regions places upper bounds on global transport rates in the cavity. The buildup of mixed area is measured and exit manifolds for lower cells are identified.

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REPORT TO THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

TRANSPORT-ENHANCEMENT IN CELLULAR FLOWS

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Chaos-enhanced transport in cellular flows - such as those generated within cavities by a top free-flowing stream - are studied with the long term objective of devising means to increase the rate of transport between surfaces and bulk flows. In several experimental cavities chaotic advection is generated by periodic modulation of the free stream velocity. We find that transport occurs only near reattachment points of wall-attached streamlines. Detailed local measurements of transport in these regions places upper bounds on global transport rates in the cavity. The buildup of mixed area is measured and exit manifolds for lower cells are identified.

There are significant benefits in managing and controlling flows and transport in the vicinity of surfaces. Of particular interest here is flow and transport in the vicinity of indentations, wedges, and cavities - patterns that might be present in structured walls and surfaces - but also in separated flows in corners, behind bluff bodies, and steps. Whereas some of these configurations can reduce drag - in spite of an increase in surface area (e.g., Walsh 1983) - they might in general, reduce transport due to the presence of wall-anchored streamlines, closed streamlines (cells), or arrays of cells of ever diminishing strength, as in the celebrated Moffatt flow (Moffatt 1964). The character of the flow is largely dictated by the dimensions of the cell and in the case of microflows - cavities in the order of 10^{-4}-10^{-5} m - Reynolds numbers of the order 10^{-3}-10^{1} are not uncommon.

The objective of our studies is two-fold: (i) to understand the basic kinematical mechanisms controlling transport in flows with closed streamlines, (ii) to investigate the possibilities for transport enhancement in such flows. For the experimental phase of this study, we take as a prototypical flow the time-dependent deformation of streamlines passing across the mouth of a cavity. This could mimic, for instance, the effect of a time-varying shear flow. Time-dependent bending creates chaotic advection within the cell and unseals separation streamlines, enabling transport. Chaos aids transport in two different ways: *locally*, it aids the local rate of diffusional transport by increasing interfacial area and increasing concentration gradients; *globally*, it diminishes global inhomogeneities by shuffling large portions of the fluid.

Representative Results

Transport measurements in a 2-cell open cavity: The cavities for experiment are rectangular of $\Gamma = 0.5$, 1, and 4, and a 90° triangle, where Γ is the aspect ratio, defined as the width of a cavity divided by its height. A wavy wall drives the flow. Each wave, as it passes over a cavity, bends the streamlines into the cavity. The wall (really a cylinder) passes at constant speed giving periodic perturbations to the cavity under study. This leads to mixing in the cavity and transport of material into and out of the cavity. The amplitude and wavelength of the waves controls the degree of perturbation, with the amplitude a normalized by the channel width in the absence of waves, and the wavelength λ normalized by the width of the cavity's mouth. Current studies have focused on the effects of amplitude changes with the wavelength held constant at $\lambda = 1$.

In the absence of perturbation, the flow in the $\Gamma = 0.5$ cell consists of two cells with wall-attached streamlines across the cavity mouth and between the cells; there is no communication between cells or the exterior flow. For any perturbation the reattachment points of the bounding streamlines destabilize, whereby dyed material initially inside the cells leaks out in visible pulses. Since the flow is area preserving, the invaded area is equal to the area transported out of the cavity by the flow. For even the largest wave amplitudes transport occurs only at these reattachment points. This appears to be a generic feature of transport in chaotic systems as other studies in this lab have also verified the especially vigorous mixing at reattachment points and especially robust stability at attachment points (Jana et al, 1994).

At these transport regions filaments of material called lobes are injected across the formally bounding streamline. These lobes are important because they are the only dynamical means of transport and they place an upper bound on transport in the cavity. Figure 1 shows a digitized sequence of a lobe forming at the downstream corner of the cavity mouth. Each picture shows the dye stream after one wave has passed over the cavity mouth. Figure 2 shows a section from a time series of the area under the dye streak in fig 1. Since the perturbations are periodic, lobe formation is periodic too. The injection frequency as well as quantitative information on the lobe area and lobe shape can be obtained from Fourier transforms of the time-series. Figure 3 shows a lobe is formed every 10 waves. Figure 4 shows a transition from a periodic to a quasi-periodic lobe as the wave amplitude increases. It is interesting that the shape transition occurs at nearly the same amplitude as the area coverage maximum previously reported.

For secondary cells transport is opened at every reattachment point. On one hand this is good news: an exit manifold immediately opens connecting every cell to every other cell and to the free stream. However, transport rates along these manifolds go as the cell circulation amplitudes, i.e. they decrease about a thousand fold for each cell lower in the hierarchy. Figure 5 shows the exit manifold for the lower cell (yellow dye) transporting material into the upper cell and out of the cavity.

Measurement of local lobe formation only tells part of the story. As they stretch and fold in the cavity, the lobe material (asymptotically) forms a stochastic network within the cavity. Depending on the perturbation more or less of the cavity becomes involved in the transport (e.g. the central island in figure 5). The overall transport efficiency is a product of both the lobe transport rate and the mixing area. Figure 6 shows the mixing area growth for a = 0.5. The saturation reflects that fact that at this amplitude even most of the upper cell material will not leave the cavity.

Other Pursuits and Extensions

Quantitative characterization of complex patterns: Trying to garner quantitative information from the cavity mixing patterns has convinced us that simple visualization is not enough. Any attempt at a deeper understanding of the relation of pattern geometry to the underlying flow requires quantitative information on evolving, complex features and transport structures. These patterns are not easily characterized by traditional methods; no technique to segment, extract, or classify features in evolving chaotic flows is very successful. Therefore, we have begun to explore techniques for the quantitative measure of complex flow structures that are often encountered in material flows involving blending, mixing, or dispersion. The techniques that currently seem most promising are the recently discovered space-scale decompositions know as wavelets and associated segmentation, texture, and pyramid algorithms.

Addendum: The results of the "Transport Enhancement" sections of this work are being prepared in manuscript form.

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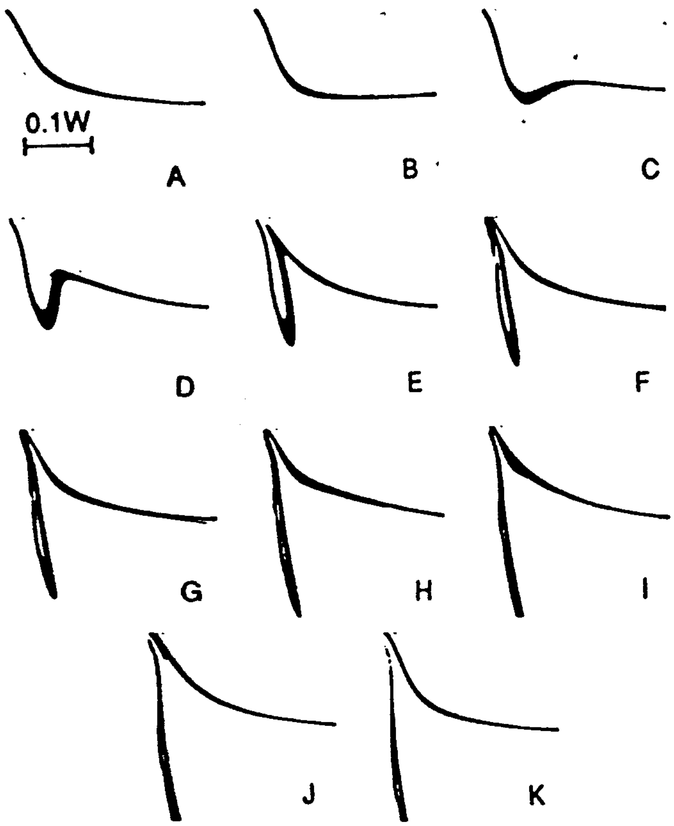

Fig. 1

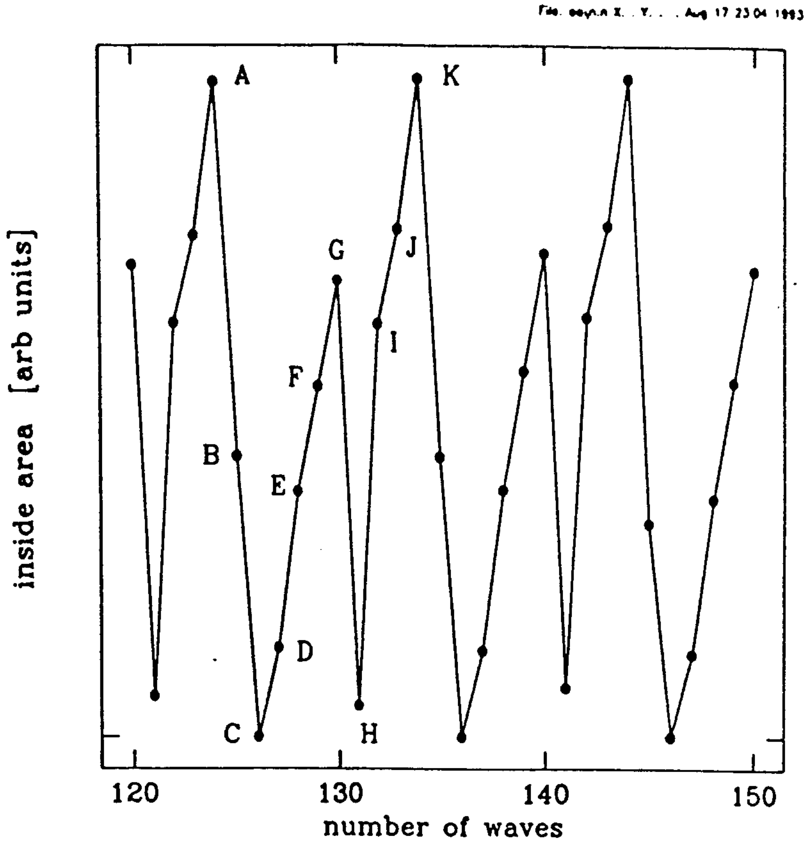

Fig. 2

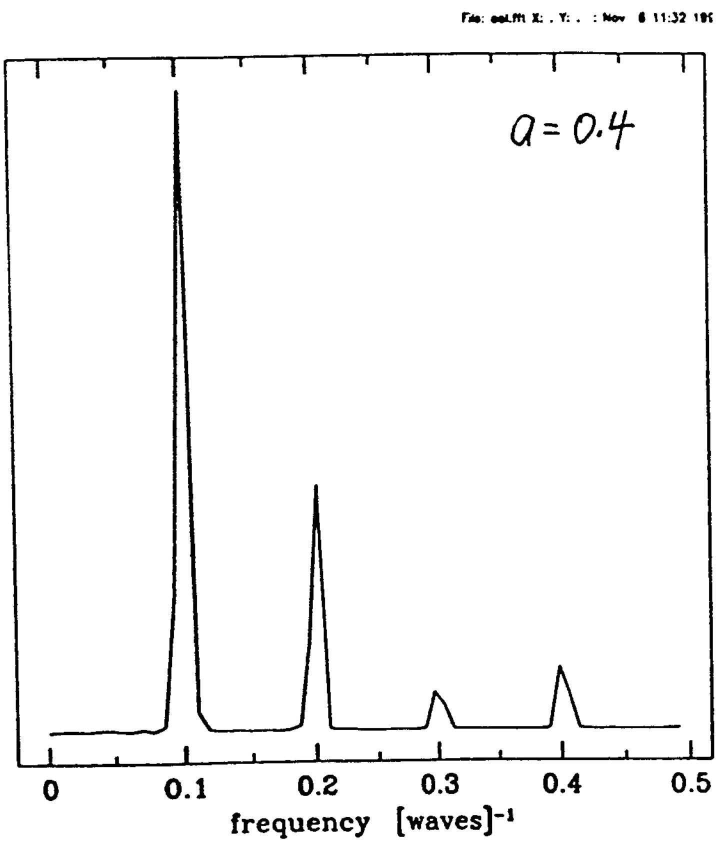

Fig 3

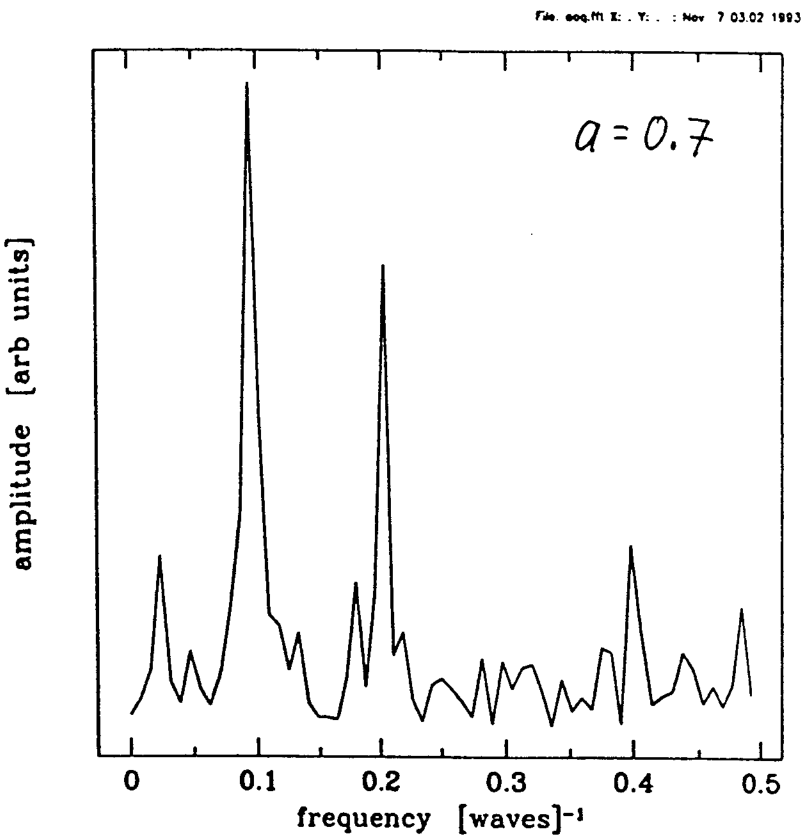

Fig 4

Figure 5

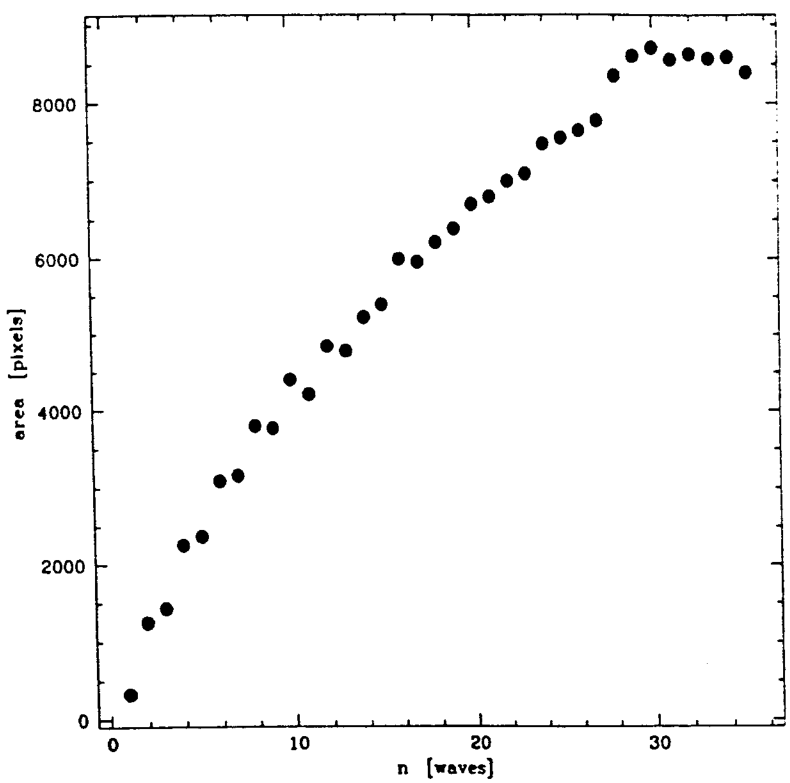

Figure 6